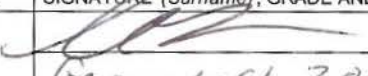


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1	DFP	sig	 Gauthier, Lt Col, 2 Oct 2014	6			
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SUMMARY

- PURPOSE.** To provide security and policy review on the document at Tab 1 prior to release to the public.
- BACKGROUND.**
Authors: M. K. Shaffer, T. C. Lilly, B.V. Zhdanov, R. J. Knize
Title: In situ non-perturbative temperature measurement in a 133-Cs alkali laser
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Description: In this paper the authors present a in situ method for determining the temperature profile of an operating alkali laser.
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- DISCUSSION.** This paper contains no material which is classified or ITAR restricted.
- VIEWS OF OTHERS.** N/A
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Tabs
1. Manuscript

In situ non-perturbative temperature measurement in a ^{133}Cs alkali laser

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Two dimensional temperature profiles of an active gain medium in a ^{133}Cs methane diode pumped alkali laser (DPAL) have been conducted. This non-perturbative technique uses a Mach-Zehnder interferometer, longitudinally coupled into the cavity of a pumped alkali laser, to probe the distortion of the optical path length in the gain medium due to heating. The resulting interferograms, captured as video, are analyzed with the commercial program, QuickFringe, to accurately measure the distortion through which the temperature profile can be determined. For a 9W ^{133}Cs + methane DPAL being pumped with 20W of resonant D1 light, a maximum temperature rise of 58.1 °C is observed. © 2014 Optical Society of America

OCIS Codes: (140.0140) Lasers and laser optics, (140.1340) Atomic gas lasers, (140.6810) Thermal effects, (120.0120) Instrumentation, measurement, and metrology, (120.6780) Temperature
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Diode Pumped Alkali Lasers (DPALs) have increasingly become the interest and focus of several research groups since their first demonstration nearly a decade ago [1]. These groups aim to realize DPALs' potential as very efficient, scalable and robust laser systems. DPALs are optically pumped 3-level laser systems, typically operating on the D₁ ($n^2S_{1/2} \rightarrow n^2P_{3/2}$) and D₂ ($n^2P_{1/2} \rightarrow n^2S_{1/2}$) lines of an atomic alkali energy structure. These systems have been practically capable of converting vast amounts of unphased, poor beam quality D₂ pump light into D₁ laser light with near diffraction limited beam quality and efficiency theoretically limited only by the quantum defect between the relevant $n^2P_{1/2}$ and $n^2P_{3/2}$ states. For Cs, Rb and K, the quantum efficiency is ~95%, 98%, 99%, respectively. Since 2003, several groups have published demonstrations for lasing of various atomic species [1, 2], verification of high efficiency operation [3, 4], output powers exceeding 1kW [5], and processes for modeling efforts [6] which strongly suggest more progress and innovations to come.

Despite these achievements, the modeling community has little benchmark data to use for validation of computational models aside from power in, power out, and some general spectral and spatial profile data with respect to the lasers. With the intention to add another benchmark for model validation, this paper demonstrates an interferometric technique which gives the temperature profile of an operating DPAL gain medium without perturbing the system.

The practice of using Mach-Zehnder interferometers to measure differences in optical path length on the order of $\lambda_{\text{probe}}/100$ or better found in numerous sources including [7]. Using interferometry to measure temperatures was first documented in 1912 by Kennard [8] and since has been expanded to measure temperatures of flames [9], heat transfer coefficients [10], and also laser gain

temperatures [11], have previously been demonstrated. This paper offers the first extension of these methods to acquire the temperature profile of an operating DPAL Cs laser. Furthermore, this work demonstrates the practicality of using the commercial wave front analysis software, QuickFringe, to simplify and expedite the process.

Theoretical Background. The premise of using an interferometer to measure relative changes in optical path length was explored several decades ago by Gower in an investigation of temperature measurements in a CO₂-N₂ TEA amplifier, where fluctuations in the index of refraction of the gases were observed during laser operation and attributed to thermal fluctuations [11]. Similarly, the approach used by Gower can be applied to DPAL systems by using an interferometer to measure the change in the optical path length through the gain medium to determine its temperature.

For an alkali gain medium cell of length L_{cell} , probe laser wavenumber, k , and initial index of refraction n_1 , the optical path length in waves within the cell and at temperature T_1 is

$$L_1 = k \int n_1 dz \cong L_{\text{cell}} k n_1 \quad (1)$$

making the assumption that n_1 is uniform and constant along the direction parallel to the axis of the cell. A similar expression describes the optical path length, L_2 , at temperature T_2 . When included in one arm of a Mach-Zehnder interferometer, heating of the laser cell results in a relative fringe shift in waves, ΔN , meaning there are ΔN less waves of the 632 nm laser light within the length of the pumped cell vs the not pumped cell such that

$$L_2 = L_1 - \Delta N \quad (2)$$

Substituting (1) into (2) and solving for n_2 gives an expression for the index of refraction at temperature T_2 as a function of the index of refraction at T_1 , the cell length, the wavenumber of the laser used in the interferometer and ΔN , the fringe shift.

$$n_2 = \frac{L_{\text{cell}} n_1 k + \Delta N}{L_{\text{cell}} k} = n_1 + \frac{\Delta N}{L_{\text{cell}} k} \quad (3)$$

The Gladstone-Dale relation describes the relationship between index of refraction and the density of a material as

$$\kappa = \frac{n-1}{\rho} \quad (4)$$

where κ and ρ are the Gladstone-Dale constant at the 632 nm probe laser wavelength and the density of the material respectively. The Gladstone-Dale constant does not vary with temperature, however the density, and consequently the index of refraction, does. For a given material, the indices of refraction of the gain medium cell, n_{T1} and n_{T2} , can be expressed as

$$\frac{(n_1 - 1)}{\rho_1} = \kappa = \frac{(n_2 - 1)}{\rho_2} \quad (5)$$

The ideal gas law, which, under the conditions found in this experiment, differs <0.01% from the real-gas correction, or Van der Waals law, is a valid assumption. Another assumption made is that the volume of the alkali medium cell is much greater than the pumped volume which allows us to assume that the pressure also does not change appreciably in the cell when it is pumped. Solving equation (5) for ρ_2 and substituting it into the ideal gas law,

$$\rho_1 T_1 = \rho_2 T_2 = \frac{T_2}{\rho_1} \rho_1 \frac{(n_2 - 1)}{(n_1 - 1)} \quad (6)$$

Solving then for T_2 and substituting in equation (6) gives an expression for T_2 in terms of the initial index of refraction, n_1 , initial temperature, T_1 , and the order of the observed fringe shift in waves, ΔN .

$$T_2 = T_1 \frac{(n_1 - 1)}{\left(n_1 - 1 + \frac{\Delta N}{L_{\text{cell}} k} \right)} \quad (7)$$

In its simplest application, equation (7) uses the measured fringe shift, ΔN , observed for a single, infinitesimal column of gain medium parallel to the axis,

essentially a small line through the medium, to calculate the relative temperature change in that column. Extending this concept in two spatial dimensions and time, by imaging the large interferogram onto a CMOS video camera, gives spatial and temporal resolution which can be used to extract much more information about the evolution of the gain medium.

Experimental Apparatus. This experiment couples a Mach-Zehnder interferometer longitudinally into the laser cavity of a Cs DPAL as a tool to measure in situ temperature changes. Figure 1 depicts the experimental setup. The interferometer was coupled into the laser cavity using two dichroic mirrors which reflect the 632 nm probe light (R=94%) and pass both the Cs laser 894 nm lasing light and the 852 nm pump light (T=99.0%). The interferometer laser was a Coherent stabilized HeNe laser producing ~10 mw of 632 nm single frequency light. After a spatial filter, the beam was expanded to have a full waist of ~1.5 cm before being coupled into the interferometer. The interferometer used two 50/50 beam splitters and a neutral density filter to ensure the recombined beams are of equal intensity to produce a high contrast interferogram. An f=200 mm lens was used to image the interferogram in the gain medium region onto a CMOS detector (Thor Labs DCC1545M) for data acquisition.

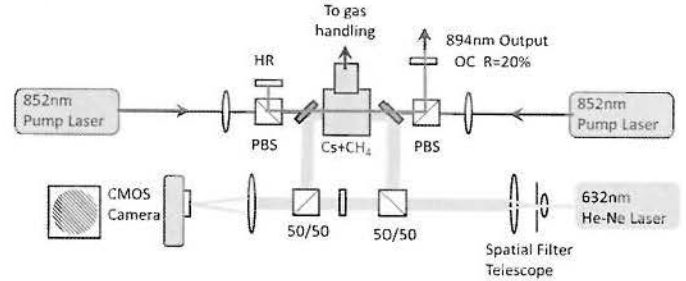


Fig. 1. Schematic of the experimental apparatus, coupling a Mach-Zehnder interferometer into an operating Cs DPAL.

The Cs DPAL was of similar geometry to that found in [12] with the exception of the glass alkali gain cell replaced with an alkali cell constructed of 1-1/3" conflat vacuum fittings, valves, and viewports, connected to a vacuum and gas handling manifold. The Cs alkali cell's AR coated viewport windows had reflective losses of 0.5%, 0.5% and 4.0% for 852 nm, 894 nm and 632 nm wavelengths respectively. The 852 nm pump lasers are two Lasertel 19-emitter LDAs which have been line narrowed to 11 GHz to match the pressure broadened D2 absorption line in Cs. Each pump produced ~10W of resonant power. The Cs laser cavity was a stable, U-shaped cavity of length 45 cm, comprised of a flat, 894 nm high reflector and an Rcc=50 cm, 20% reflective output coupler. The 4.3 cm long gain cell was placed 32 cm from the flat high reflector where the laser cavity mode half waist ranged from ~0.50 – 0.55 mm over the length of the cell and best matched the pump laser half waist. The focused pump beams had a rectangular, semi-top hat profile and half waists in the horizontal and vertical directions of 0.525 mm and 0.580 mm respectively. The

pump focus also had a slight astigmatism where position of the focus in the vertical and horizontal directions differed by 2 mm. The pump beams, which were polarized orthogonally to the polarization of the alkali laser cavity were coupled into the alkali laser cavity using polarizing beam splitter cubes.

The vacuum alkali cell was detached from the vacuum system at the right angle valve and filled with dry nitrogen and ~ 0.25 g of Cs while in a glove box. The right angle valve of the sealed cell was then reattached to the nitrogen purged vacuum system, opened, and then pumped down to $<10^{-7}$ Torr for several hours. The vacuum system was then sealed and back filled with 600 Torr of UHP grade methane at a room temperature of 21°C . The right angle valve of the alkali cell was then sealed and the remainder of the vacuum system evacuated to prevent heat transfer on the back of the seal due to a cold buffer gas. The cell and nearby vacuum components were outfitted with resistive heaters and wrapped in foil to promote uniform heating throughout the cell body. The cell was then heated to 110°C (383 K) with the reservoir held at 96°C (369 K) for optimal Cs laser operation.

Experimental Procedure & Results. The 632 nm HeNe laser for the interferometer was turned on and allowed to stabilize. The interferometer geometry was set such that the generated interferogram on the CMOS camera revealed roughly 25 fringes in the field. The CMOS camera then began recording the interferogram at 20 Hz as the Cs + CH_4 gain medium was longitudinally pumped with 20 W (10 W from either direction) of narrowband D2 852 nm laser light. The Cs laser output was recorded at 9.5 W of D1 894 nm. After 5 seconds, the pump lasers were blocked and subsequently the camera recording was stopped. The experiment was run again with pump light deliberately tuned off resonance from the D2 Cs line to assure distortions observed in the interferogram were the result of gain medium heating from laser operation.

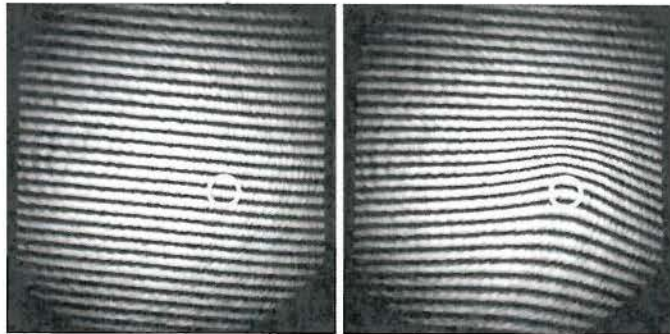


Fig. 2. Two interferograms of the gain medium within the Cs DPAL gain cell. The left image is taken as a reference without the pump beams on, the right image is taken 0.5 seconds after the pump beams have been turned on and the system is lasing. The yellow circle denotes the ~ 1.1 mm beam waist of the laser cavity.

Video editing software was then used to review and select two frames from the recording: one taken prior to pumping the gain medium that would serve as a reference interferogram (Figure 2 left), the other frame was taken

10 frames (~ 0.5 seconds) after pumping and lasing were initiated (Figure 2 right). For clarity, the laser cavity mode diameter is depicted as a yellow circle in both figures. By visual analysis of these images alone, the distortion in the wavefront is evident. To gain a quantitative result from the images we employ the interferogram and wavefront analysis software, QuickFringe. By inputting a reference interferogram and an experimental interferogram, this software determines the wavefront distortion in number of waves, ΔN , of the laser used in the interferometer, presenting it as a 2D array.

Using equation (7), an ambient temperature 383 K , a cell length of 4.35 cm and ΔN as given by QuickFringe, the corresponding temperature profile of the active gain medium, averaged along the longitudinal axis, was calculated and is presented in Fig 3. The index of refraction of the methane + Cs medium is largely dominated by methane, $n_1 = 1.0003222$, which is adjusted from the referenced value of $n=1.000444$ due to the temperature and pressure variations between the reference conditions, 760 Torr at 0°C , and our experiment, 600 Torr at 21°C . Note that index relates to density and therefore temperatures refer to gas fill temperatures.

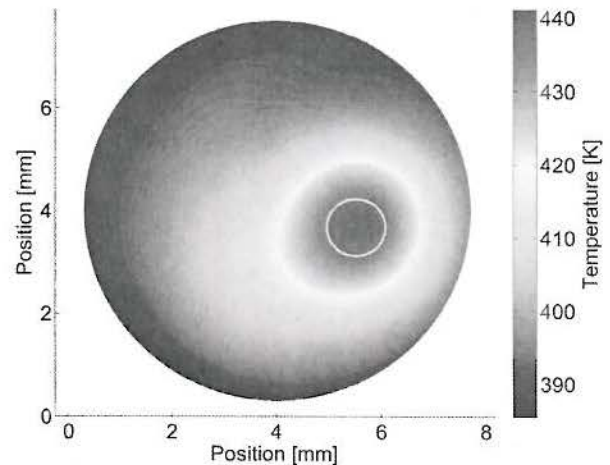


Fig. 3. Longitudinally averaged temperature profile derived from interferogram. Note beam waist indicated by white circle.

The maximum ΔN determined by QuickFringe was 2.92, corresponding to a maximum temperature rise of 58.1°C , or a maximum temperature of 168.1°C . The general shape of the temperature profile is to be expected and it emphasizes that much of the surrounding gain medium, >5 laser mode diameters away, still experiences elevated temperatures. Though the video is not included here, it should be noted that no strong convective currents in the buffer gas were observed, which suggests the primary mechanism for removing heat from the pumped gain medium at these powers is thermal diffusion.

Concluding Remarks. A technique to directly, and non-perturbatively, measure the temperature profile of the gain medium of an operating DPAL has been

demonstrated using interferometry. The use of the wavefront analysis software QuickFringe and simple mathematical expressions allow for a 2D temperature profile of the gain medium to be determined rapidly. The information gathered through the steady state or, though not demonstrated here, time dependent temperature profiles can be useful to the DPAL modeling community. The temperature profile and the maximum temperature reached have several implications in laser operation that should not go without mention, mostly with regards to power scaling.

First, at the heart of this measurement it is a wavefront distortion caused by variation in the index of refraction that allows for the extraction of temperature within the medium. If the distortion has strong curvature over the mode of the laser, thermal lensing will be observed in the DPAL output beam. The wavefront distortion over the 11 mm mode diameter in this experiment was $\sim \lambda/3$.

Second, the methane density decreases with increased temperature. While in competition with increased collisions due to thermal motion, the decrease in density will result in decreased fine structure mixing rates. Additionally, the alkali density will also deplete in response to the temperature increase. In extreme cases, both of these effects could lead to significantly depleted small signal gain.

Third, specifically in regards to DPALs using hydrocarbon buffer gases, the increased temperatures of the methane in the center of the pumped region may lead to increased dissociation rates. Dissociation, which for methane begins to slowly occur at roughly 150°C, will not only deplete the mixing gas density, but may result in new, unintended species of methyl radicals or alkynes such as acetylene, that can serve to quench the excited $^2P_{3/2,1/2}$ states [13]. Another reaction that may warrant consideration is the production of Cs hydride. Both of these effects can potentially degrade DPAL performance.

While this technique has been applied to the static DPAL, it may be directly applied to the flowing DPAL system as well, but not without the additional complications of density variations within the flow.

Uncertainty Analysis. Several systematic errors are introduced into the determination of T_2 by assumptions and approximations in the theoretical treatment, though most of the associated errors are much smaller than the imprecision errors accrued during measurements of T_1 , L_{cell} , and Δn . The error introduced by using the ideal gas law in lieu of more accurate Van der Waals gas law for determining density of methane at experimentally relevant values of methane pressure, temperature and volumes is negligible (0.0004%). Another assumption made is that the pressure remains the same when the gain medium is pumped. The mode volume in the gain medium is $4.3 \text{ cm} \times \pi (0.05 \text{ cm})^2 = 0.034 \text{ cm}^3$ while the cell volume is estimated to be 62 cm^3 . At the limit of having the pumped mode volume completely evacuated, this would at most introduce $\sim 0.05\%$ error in T_2 . Measurement of L_{cell} was done prior to assembly of the cell

by measuring the components of the cell with a Vernier caliper accurate to 0.01 mm, however after assembly, filling and heating of the cell, we estimate L_{cell} is known to $\sim 1.2\%$. The determination of Δn , aided dramatically by the QuickFringe software analysis, is estimated to have an uncertainty in relative $\Delta n < 0.5\%$ in waves, largely driven by the uncertainty in fringe location in the interferogram. Uncertainty in the quantity index of refraction minus one, $n_1 - 1$, is $< 0.2\%$, reflecting variation in the index due to the uncertainty in the methane pressure of 600 Torr as measured by a heated Baratron capacitance manometer. Added in quadrature, the total error is approximately 5.2%.

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